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# **Implementing hygromorphic wood composites into responsive building skins**

Artem Holstov, PhD Candidate

School of Civil Engineering and Geosciences, Newcastle University, UK

artem.holstov@newcastle.ac.uk

Graham Farmer, Prof., Head of Architecture

School of Architecture Planning and Landscape, Newcastle University, UK

graham.farmer@newcastle.ac.uk

Ben Bridgens, Dr., Lecturer in Structural Engineering

School of Civil Engineering and Geosciences, Newcastle University, UK

ben.bridgens@newcastle.ac.uk

## **Abstract**

Natural organisms which employ inherent material properties to enable a passive dynamic response offer inspiration for adaptive bioclimatic architecture. This approach allows a move away from the excessive technological intensity of conventional 'smart' building systems towards a more autonomous and robust materially embedded sensitivity and climatic responsiveness. The actuation mechanisms of natural responsive systems, such as moisture-induced movement of bilayered conifer cone scales, can be replicated to produce artificial moisture-sensitive (hygromorphic) composites with the response driven by hygroexpansion of wood. The developed low-tech low-cost hygromorphic materials are capable of pre-programmable reversible mechanical response to changeable levels of ambient humidity and moisture. Previous research into hygromorphs has provided the theoretical basis for rational selection of composite configurations, including the choice of material for each layer, their thicknesses, orientation and type of bond. This paper explores the opportunities and challenges for building integration and architectural functionalisation of the responsive wooden composites. The suitability of different material production techniques and viability of potential applications is established through a detailed programme of experimentation and long-term field tests.

## **Keywords**

hygromorphic wood composites; reversible moisture-induced response; low-tech low-cost smart materials; passive climate-responsiveness; biomimetic architecture; sustainable adaptive building skins

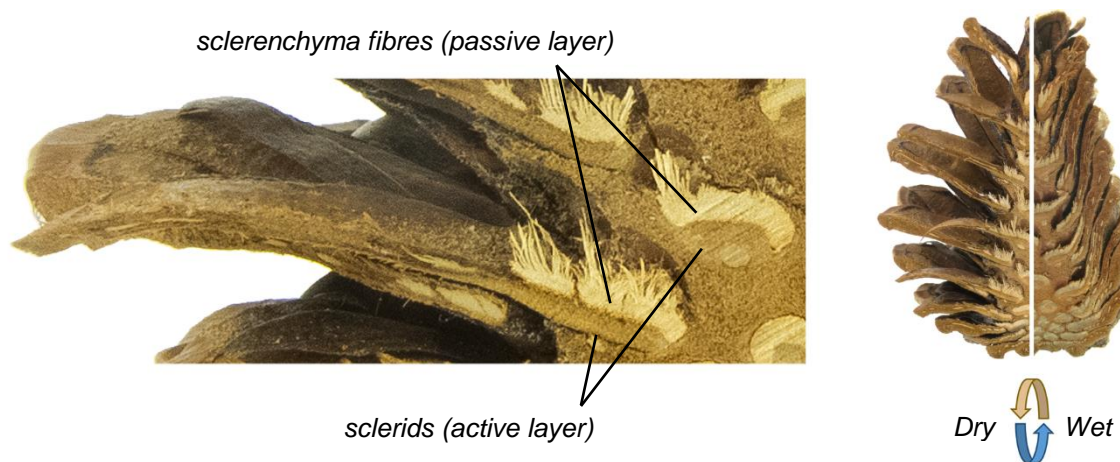
## **1. Re-shaping adaptive architecture with responsive wood composites**

### **1.1 Ecologically embedded versus technologically imposed response**

Adaptive building systems capable of real-time automated response to changeable environmental conditions and building use can improve a building's energy performance and facilitate enhanced occupant comfort [1]. This can be achieved by means of synchronization and advanced automation of active (i.e. energy-dependent) building systems [2], including lighting, heating, ventilation and air conditioning and super-imposed dynamic features, such as automated louver shading. In contemporary adaptive architecture the intelligent climatically responsive behaviour is driven by the interaction of separate mechanical and electrical components performing the sensing, processing, controlling and actuating functions [3]. This results in high complexity and technological intensity of the conventional adaptive systems reducing their cost-effectiveness and reliability and preserving their reliance on external energy supply. Benefits of high-tech intelligent building technologies and zero-energy passive design can potentially be combined in adaptive systems where the response is implemented by smart materials with embedded sensitivity to climatic stimuli. The inspiration for material

fabrication techniques and response mechanisms, which can be employed for this ‘hybrid’ design approach, can be drawn from biological systems that function reliably in the conditions of limited resources and are relied on efficient processes of energy conversion [4].

Examples of such natural responsive systems include a number of plant species that have evolved functional mechanisms of repeated moisture-induced shape morphing enabled solely by inherent hygroscopic properties and intricate hierarchical structure of their tissues. For instance, opening of seed-producing scales of conifer cones in dry environment actuates the dispersal of ripe seeds ensuring favourable conditions for their germination [5]. This mechanism results from bilayered structure of the scales consisting of cells with different orientation of stiff cellulose microfibrils (CMFs), which exhibit large transverse and small longitudinal swelling and shrinkage (hygroexpansion) [6, 7, 8] (figure 1). The anisotropic dimensional changes of CMFs are translated into differential hygroexpansion of the scales’ layers which results in bending. The response of conifer cones is reversible and repeatable over a large number of cycles even after the seeds are released and the tissues of the scales are biologically dead [3].



*Figure 1: Moisture-induced opening and closing of pine cones enabled by bilayered structure of the base of seed-producing scales.*

The ability to convert relatively small unidirectional dimensional changes into geometrically amplified movement permitted by the bilayer principle is also observed in a number of other natural systems, such as wheat awns [9], orchid tree seedpods [10], seed capsules of ice plants [11] and stems of spikemoss [12]. This principle can be adopted to produce artificial materials with programmable reversible moisture-induced response (a.k.a. hygromorphs) consisting of hygroscopic active layers, and passive layers, which provide constraint to planar hygroexpansion and force the composites to bend. The development and potential application of hygromorphic materials in adaptive building skins provides opportunities for design of passively responsive bioclimatic architecture that is in constant synchronization with variable levels of atmospheric humidity and ambient moisture which is visually expressed on the building facade.

## 1.2 Wood versus synthetic active layers

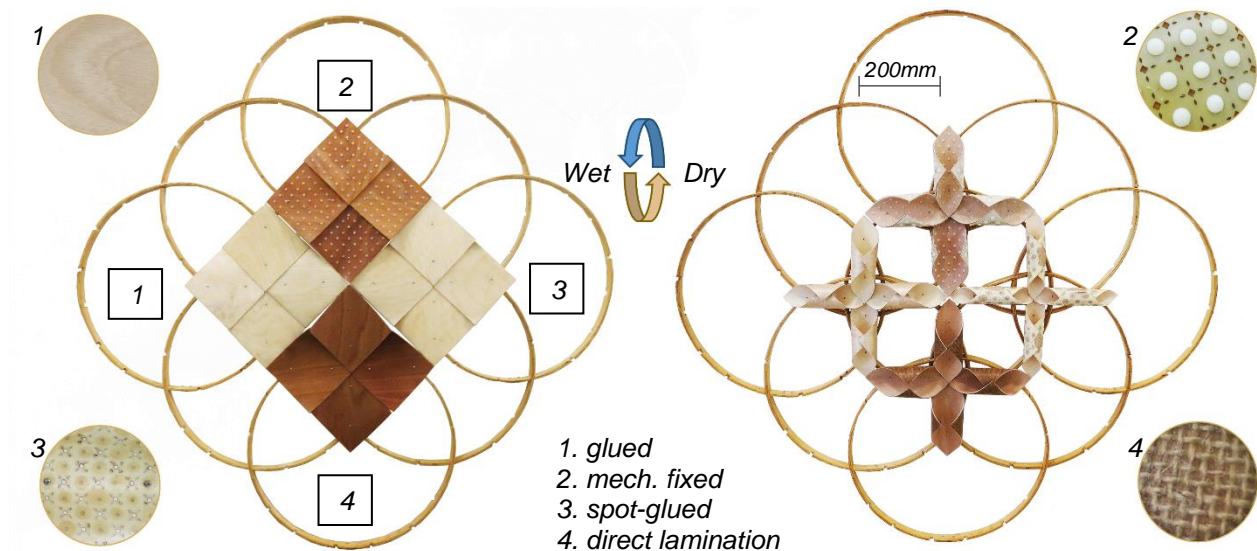
One of the main challenges for development of hygromorphs suitable for building integration is the possibility of up-scaling their size and mechanical strength to meet the requirements for large scale applications, whilst retaining sufficient responsiveness [13]. The fulfilment of these criteria depends on the ability of the active layer to produce substantial hygroexpansion and generate enough force to drive the curvature changes of the composites. Wood is one of few natural hygroscopic materials which encompasses these characteristics and, in fact, greatly surpasses the combination of strength properties and magnitude and speed of moisture-induced response achievable with many synthetic alternatives [14], such as hydrogels [10], electro-active and layer-by-layer deposited hygroscopic polymers [15, 16] and bacterial spores [17]. This points to good applicability of wood for active layers of hygromorphs.

In the last decade, rapid advancements in material fabrication technologies have enabled the production of hygromorphic materials with synthetic active layers mimicking the natural structure of wood. This can be achieved through embedding of oriented natural or synthetic cellulose-rich fibres within a hot-pressed [18] or 3D printed [19] polymer matrix. The main advantages of this approach are consistent properties of raw materials and the ability to adjust the direction of the fibres. However, the response speed of the resulting composites is reduced due to limited hygroscopicity of polymer-coated fibres [19]. In contrast, wood as a functional tissue of trees is naturally provided with multiple passageways for water adsorption and transport. In addition, it exhibits a pronounced trilinear anisotropy (orthotropy) in many of its properties, including hygroexpansion [20], which helps prevent the undesirable effects of double curvature observed in composites with homogenous volumetric expansion of active layers [21]. The ability to choose an active layer from a wide range of commonly available wood species with different properties and different types of cut provides additional means to tune hygromorphs' response and tailor their durability and appearance for different applications [21]. The use of the widely available naturally formed biodegradable material with an ecologically embedded responsiveness as a key component of the composites reduces their environmental impact and helps decrease the complexity of material fabrication.

## 2. Addressing challenges in design and production of hygromorphs

### 2.1 Methods of material fabrication

The production of wood composites capable of withstanding the internal stresses resulting from differential hygroexpansion in multiple cycles of response without delamination requires the selection of fabrication methods that simultaneously provide high strength, stiffness and durability of the interfacial bond between the layers [21]. At the same time, negative effects of the bond on the response size and speed have to be minimised. Four different methods of material fabrication have been tested, including gluing, mechanical fixing and spot-gluing of rigid passive layers and direct lamination of engineering- and bio-fabrics (Figure 2).



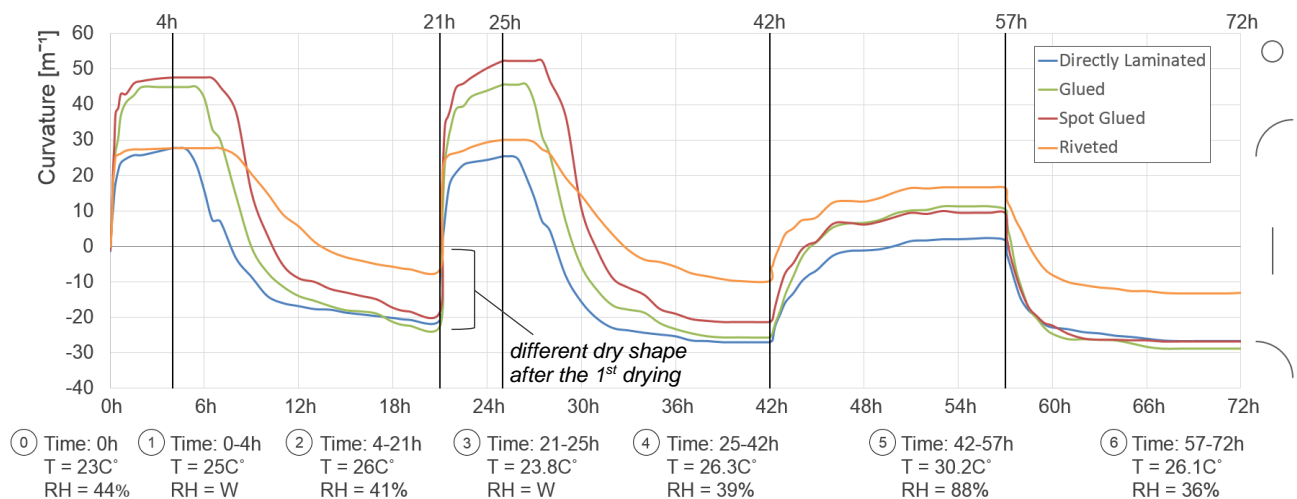
*Figure 2: Demonstration prototype incorporating responsive panels with four different types of layer bonds. The passive layers are shown in the numbered circles (1 – wood, 2 and 3 – fiberglass and 4 – jute fabric).*

Gluing enables the production of a wide range of semi-synthetic hygromorphs with polymer, fiberglass or other synthetic passive layers and cross-grained laminates consisting of two wooden layers with different grain directions, such as in figure 2 panel type 1. However, the choice of applicable adhesives is limited due to stringent requirements for their water-resistance and mechanical properties when cured at high relative humidities and with substrates that have a high moisture content (MC). It has been experimentally established that only some high-performance structural adhesives, which cure at room temperatures, can meet these requirements. These include selected two-part epoxies and polyurethane glues, such as Permabond ET5428

and Purbond HB-S309 respectively. Yet, none of the tested adhesives are effective when used with damp fully expanded wooden layers that have MC above ~30% (fibre saturation point, MC<sub>f</sub>). Once the adhesives come in contact with free water within wood, their dissolution leads to decreased viscosity resulting in excessive penetration and staining of the active layer as well as loss of the bonding strength. Microscopic examination of the composites with glued layers has shown that the selected adhesives, which have dynamic viscosity ranging from 20000mPa.s to 35000mPa.s at application in room conditions, permeate the cavities of only the wood cells that are adjacent to the glued surface with the rest of the active layer unaffected. This minimises the unwanted reduction in the hygroscopicity of wood, which is the largest constraint for the use of low viscosity adhesives, such as cyanoacrylates, in the production of hygromorphs.

The need for a separate glue layer can be eliminated if a reinforcing fabric, such as interwoven glass fibers or natural bio-textiles, is laminated directly onto wood using liquid epoxy or bio-resin. Excessive soaking and starvation of the resin matrix can be prevented by pre-coating the active layer. However, due to precise timing required to ensure that the preliminary epoxy coating achieves just the right viscosity before lamination of the main passive layer, this extra production stage adds significant complexity to the fabrication. The use of bio-textiles, such as jute (figure 2 panel type 4), flax or hemp, can reduce the environmental footprint of directly laminated composites, but almost inevitable variations in the MC of the hygroscopic fibres can lead to their detachment from the epoxy matrix [18] and undesired changes in the properties of the passive layer. A common characteristic of the standard gluing and direct lamination production techniques is that the passive layer remains impermeable to water, and moisture exchange only happens through one side of the active layer which slows the response.

Mechanically fixing the composite layers guarantees that the issues of reduced hygroscopicity of wood and delamination are avoided. This method is well-suited for automated production and enables replacement and reuse or recycling of the layers. The passive layer can be perforated between the points of connection allowing moisture access through both sides of the composite. The integrity and quality of the riveted (figure 2 panel type 2) or bolted connections is independent from the moisture content of the layers meaning that even wet wood can be used. Mechanical layer fixing methods are most applicable for hygromorphs with relatively thick active layers (above ~3mm) due to the connections creating points of local stress concentrations, which can lead to cracking of wood veneer along the weaker longitudinal grain direction. Thin wood veneer can still be coupled with perforated passive layers if the mechanical connections are replaced with a pattern of separate glued areas to facilitate an improved distribution of the interfacial forces during the response (figure 2 panel type 3). The resulting spot-glued composites have the overall highest response speed among the composites with analogous configurations and, owing to comparatively small amount of trapped water between the layers, they are noticeably quicker to dry from a wet state than hygromorphs with mechanical fixings (figure 3).



**Figure 3:** Average response of 150mm long 100mm wide samples of hygromorphs with four different types of layer bonding, but otherwise identical or analogous configurations, to cycles of wetting and drying and changeable ambient humidity. The tested composites consisted of 1mm rotary-cut silver birch active layers and 0.2mm rigid or 300gsm laminated epoxyglass passive layers.



The experimental results show that the choice of material fabrication method affects both the speed and magnitude of the response. The reduced responsiveness of mechanically fixed and directly laminated composites results from local buckling of the active layer between the fixing points and differences between the stiffness of rigid and laminated epoxyglass layers respectively. Responsiveness of hygromorphs can be adjusted through selection of material configurations with different thickness, stiffness and hygroexpansion of the layers [21].

## 2.2 Response pre-programming

Identical configurations of hygromorphs can be pre-programmed to exhibit response within different curvature ranges depending on application requirements. The pre-programming is applied during the material fabrication by pre-conditioning wood to a specific moisture content, setting the initial shape of the composites, using pre-stressed layers or a combination of these methods. For instance, hygromorphs with mechanically fixed layers can be pre-programmed to assume a straight shape in wet conditions if the initial production MC of the active layer is equal or greater than MC<sub>f</sub> and the layers are joined flat. Despite the inability to glue wet wood, the same pre-programming can be achieved with glued, spot-glued and directly laminated composites if the wooden layers are pre-conditioned at high relative humidity and the materials are set into a slightly curved initial shape with the passive layer on the convex side (negative curvature). These pre-programming methods have been used for panels of prototypes 'a' and 'c' in figure 5. Whilst the composites prepared with saturated or nearly saturated active layers produce a consistent reversible response to cyclic wetting, drying and changeable ambient humidity, thin initially straight hygromorphs fabricated in room conditions exhibit a distinct difference between the first and subsequent response cycles returning to a reversely curved shape after the first drying (figures 3 and 4). There is also a noticeable, albeit less pronounced, tendency for the response of these composites to shift towards a lower or more negative curvature with each consecutive response cycle. Conversely, it has been observed that hygromorphs with comparatively thick dry-bonded active layers (above ~5mm) gradually obtain positive dry curvature after the first few wetting and drying cycles. This points to the possibility of selecting a 'balanced' intermediate active layer thickness enabling a consistent cyclic response of dry-bonded hygromorphs. This principle has been employed when configuring the responsive panels used for prototype 'd' in figure 5. Alternatively, the inconsistencies in the response of the thinner composites can be compensated by reducing the production MC of the active layer, preparing the composites with a positive initial curvature or using pre-tensioned passive or pre-compressed active layers. The first two of the above calibration methods have been used for pre-programming of the panels in prototype 'b' in figure 5.

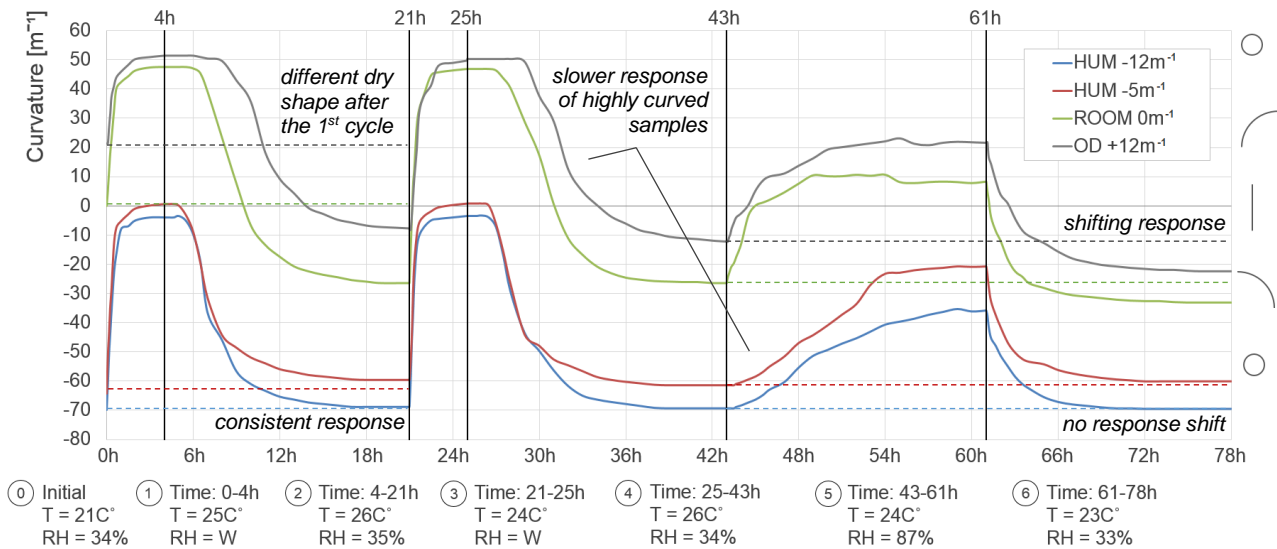


Figure 4: Average response of samples of hygromorphs with different pre-programming, but identical dimensions and configurations (same as glued composites in figure 3). Different initial curvature 'x m<sup>-1</sup>' and active layer pre-conditioning, where 'HUM' is ~90%RH at 23°C, 'ROOM' is ~35%RH at 23°C and 'OD' is oven-dried at 65°C, have been applied for pre-programming.

### 2.3 Response mechanisms and material durability

Adjustment of the geometry and arrangement of hygromorphic composite panels and orientation of the layers, including the direction of wood grain, allows transformation of local curvature changes of the materials into a range of shape-morphing mechanisms involving different combinations of bending and twisting [10, 14]. The resulting movement can be employed to drive porosity changes of adaptive skins [22], actuate larger non-responsive elements [13], enable self-assembly of various constructs [14] and even power rotary or crawling locomotion [17]. The tunable and scalable response of the materials provides multiple opportunities for unique and creative designs of adaptive building skins with hygromorphic cladding. Figure 5 below shows two possible cladding designs where the arrangement of overlapping responsive panels, inspired by lizard skin ('a' and 'b') and rectangular roof tiles ('c' and 'd'), provides full surface coverage in pre-determined ambient conditions allowing such potential applications as self-sealing cladding of a semi-conditioned rain shelter. Both of these designs are based on repeated patterns of identically sized panels facilitating simplified production.

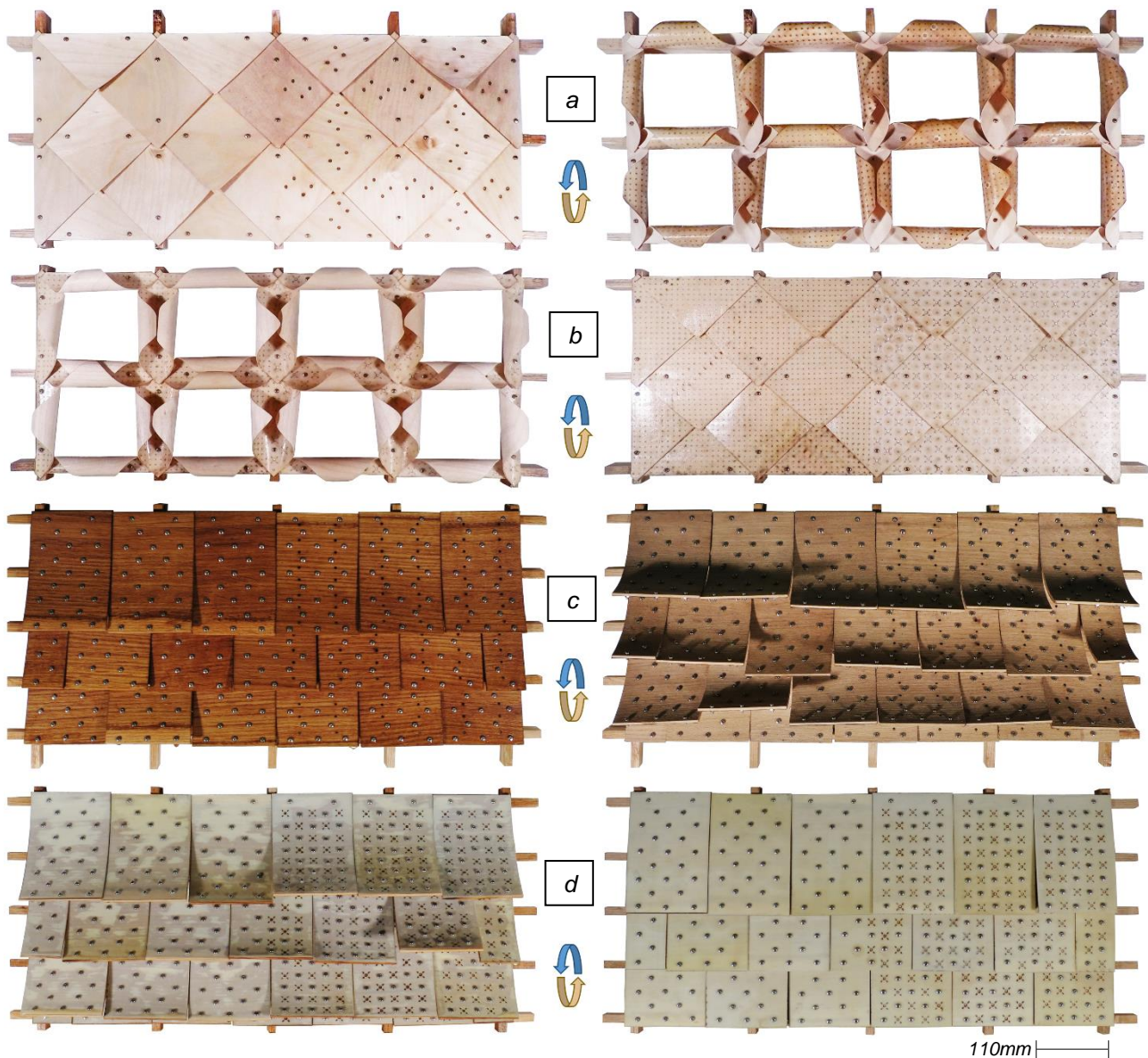


Figure 5: Prototypes of responsive cladding modules with different layer configurations and opposite pre-programming of panels in wet (left) and dry (right) conditions. The left and right sides of the prototypes consist of panels with standard and perforated active ('a' and 'c') and passive ('b' and 'd') layers respectively. The configuration of thin panels ('a' and 'b') is the same as glued composites in figure 3. Thick panels ('c' and 'd') comprise of 3.2mm thick quarter-cut English oak and 0.35mm epoxyglass layers.



Since moisture is relatively quickly transferred across the small thickness of veneer layers in cladding modules 'a' and 'b' in figure 5, the response speed of thin panels is significantly increased only when the perforation is applied to the passive layer. Selective perforation of passive layers in overlapped diamond-shaped panels ('B' in figure 6) has been used to ensure a correct sequence of their response. The reactivity of thick panels in prototypes 'c' and 'd' is not affected by additional perforation of either of the layers as moisture access throughout the composites is already enhanced by the gaps at bolted connection points.

The robustness of the developed shape-shifting mechanisms, long-term material durability and response speed to natural weather patterns have been tested over a period of seven months with the responsive panels and samples exposed to full weathering conditions on a building roof (figure 6 'A'). No preservative treatment has been applied to prevent reduced hygroscopicity of wood. Despite signs of weathering and fungi-induced colour changes, especially apparent on composites with perishable silver birch active layers (figure 6 'B'), all tested hygromorphs have retained their full responsive capacity. The rate of moulding of composites with English oak and European larch active layers, classed as resistant and moderately resistant to fungi-induced degradation [23], is much slower and small mould specks on these panels are only evident on close inspection (figure 6 'C'). It is also notable that composites with 'flat when wet' pre-programming ('PREP W' in figure 6 'C') that have wooden layers on top demonstrate higher susceptibility to moulding. Other signs of aging are limited to local cracks of thin veneer layers around panel fixings, UV-induced yellowing of epoxyglass and discoloration and staining of wood caused by leakage of extractives neither of which have affected the response. The observed weathering rates suggest a projected ~1-year usability lifespan for hygromorphs with perishable wood layers and 2-year or above for composites with naturally durable wood used outside. An improved longevity of the materials can be expected if they are protected from wetting or deployed indoors.

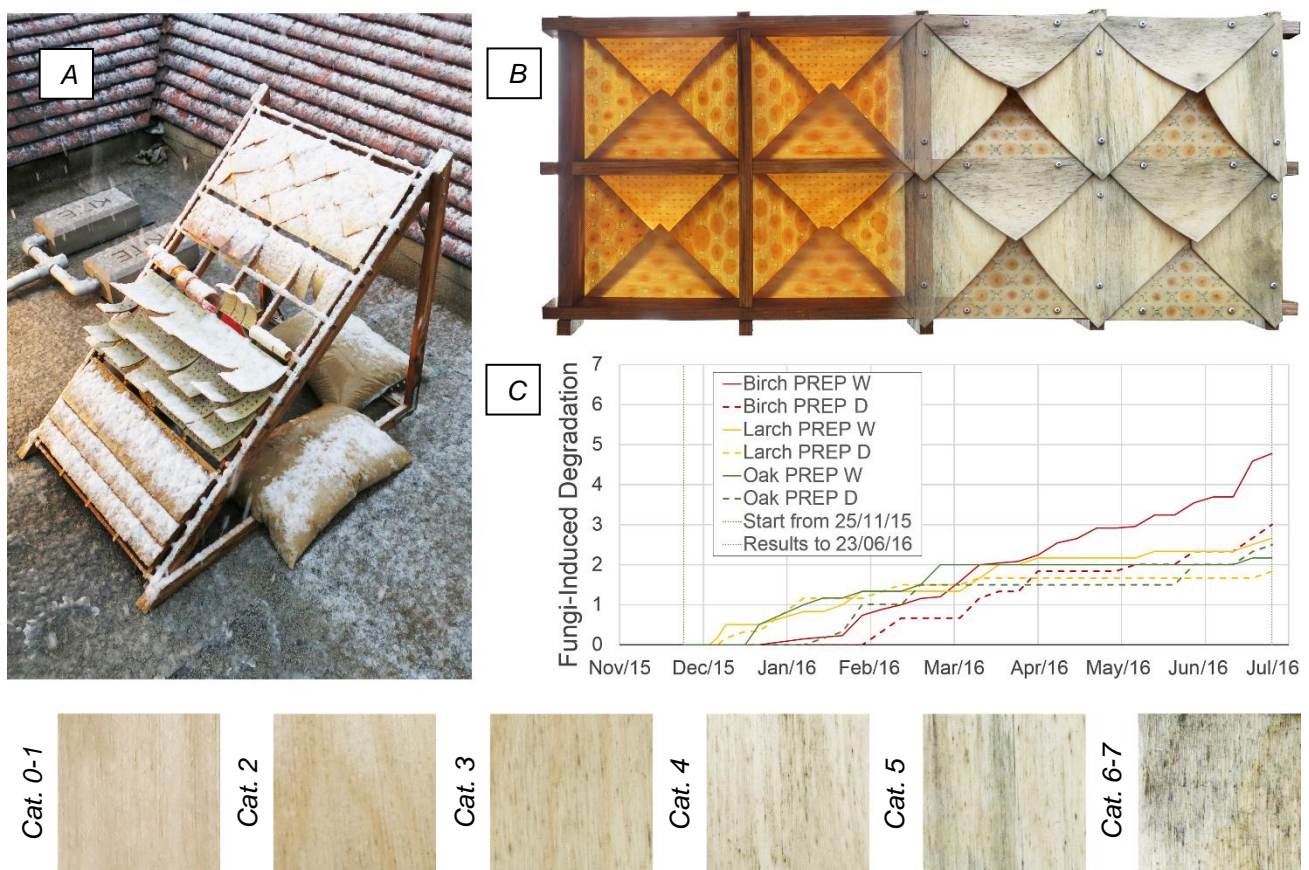


Figure 6: A – outdoor testing prototype incorporating responsive cladding modules and samples with different material configurations and pre-programming; B – responsive cladding module with improved arrangement of thin panels in closed wet state after seven months in full weathering conditions; C – time plot of fungi-induced moulding of the panels and samples assessed weekly based on the illustrated categories (0 - 'free of visual signs of mould' to 7 - 'above 75% covered with mould affecting mechanical integrity or responsive capacity' ).



### 3. Potential applications

#### 3.1 Synchronised climate-responsiveness

Continuous monthly interval photography of the outdoor testing prototype paired with simultaneous measurements of weather data have helped assess the degree of synchronisation between the dynamic behaviour of the materials and natural variable rhythms of local outdoor climate in Newcastle upon Tyne, UK. Changes in ambient relative humidity and direct contact with condensed or precipitated moisture are the main climatic stimuli for response of hygromorphs, but the rates of moisture exchange between the active wooden layers and ambient environment are also influenced by air temperature, solar irradiation and wind speed. The thinner hygromorphic panels and samples have demonstrated an ability to react swiftly to sporadic short-term precipitation and follow repeated diurnal cycles of humidity changes, which are most pronounced in the summer months when the average difference between humidity at night (higher) and during the day can reach 25%. Increased relative humidity before rain initiates transformation of the responsive cladding in advance. This preliminary response can benefit applications that require a quick formation of a rain-proof barrier (figure 7 'A'). Among other factors, the response rate to relative humidity is affected by curvature of the composites (figure 4) as twisted panels can physically confine the active layers. Slower response of the thicker panels allows adhering to longer-term relative humidity patterns or only respond fully during prolonged periods of precipitation or drought. In the North-East of England, where relative humidity average during the winter months approaches 90% and frequency of rainy days is similar across different seasons, the thicker composites may only achieve their dry shape during several continuously dry weeks in summer. This can enable their application for cladding of log drying sheds or other structures that can benefit from passive automated ventilation enhancement in dry weather. Weather dependant behaviour of hygromorphs predisposes their region-specific applications. For instance, thick composites with slow gradual response can be used in climates with distinct rainy seasons, such as San Francisco, US and Jakarta, Indonesia [24], for large landscape scale flood warning and alleviation. The materials can also be deployed in a range of indoor adaptive systems responding to building occupancy and use, such as increased humidity during public gatherings (e.g. in churches) or vapour resulting from cooking or showering (figure 7 'B').

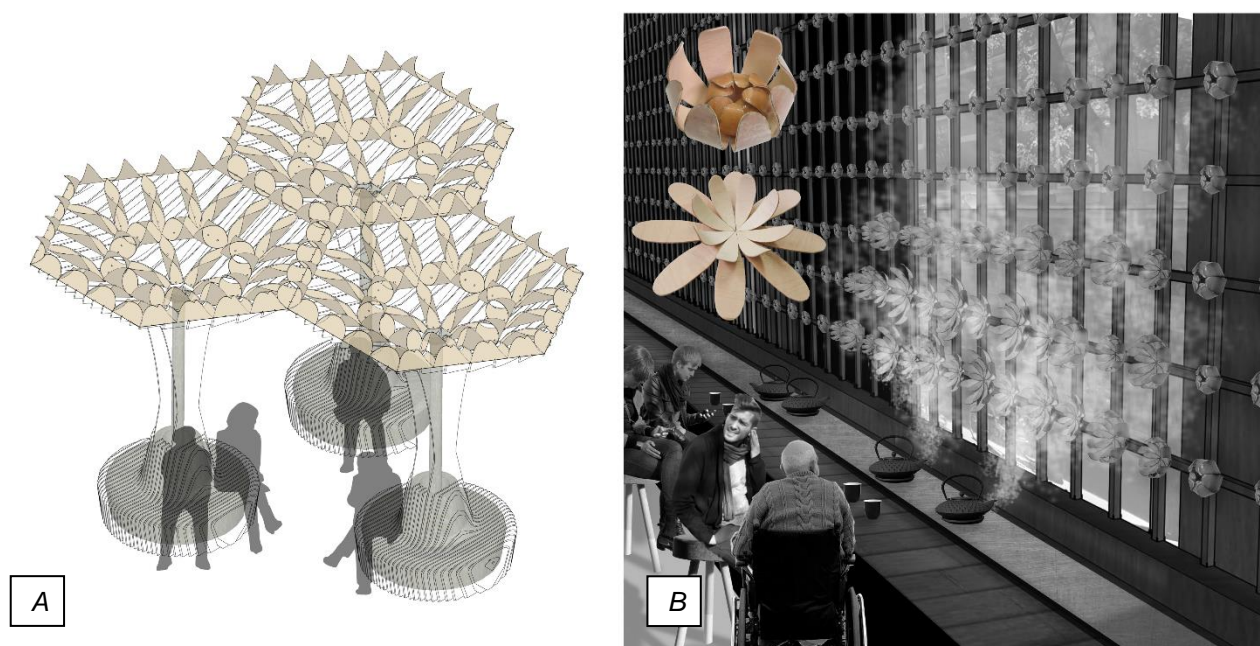


Figure 7: A – design concept of modular outdoor seating with a responsive canopy roof and an integrated drainage and rainwater collection system; B – artistic render of a teahouse with interior wall cladding comprised of responsive elements designed to imitate opening and closing of tea-flowers.

#### 3.2 Typology of applications: merging design philosophies

One of the fundamental challenges for the future development and building integration of hygromorphic wood

composites is understanding and exploiting the potential of this technology to address a multidimensional range of sustainability concerns beyond energy efficiency and enhanced performance of adaptive skins. A review of current research and literature suggests that there are potentially four overlapping typologies of applications for hygromorphs:

1. Functional devices / components (actuators, micro-generators, sensors, locomotion engines etc.);
2. Performance-oriented adaptive systems (enhanced occupant comfort, energy efficiency etc.);
3. Formal / Aesthetic value (enhanced visual appearance of a dynamic building skin);
4. Contextual / location-specific value (buildings as a physical representation of local environment and climate).

The existing research tends to be narrowly focused on discrete functional applications (1.) and aesthetic appeal of kinetic architecture (3.). The advantages of hygromorphic materials over conventional electro-mechanical smart systems, such as their low cost, technologically simple production, the use of natural locally available materials and passive ecologically embedded response, provide opportunities for more integrative design approaches that merge the functional, aesthetic and philosophical values of adaptive architecture. A key principle of this research is a recognition of cross-disciplinarity as an essential part of these design approaches. This work has started a series of collaborative teaching and research projects between engineering and architecture students and academics exploring the diverse potential benefits of hygromorphs at Newcastle University. The next step in this work is the integration of the developed hygromorphic wood composites into a permanent nature / bird watching observatory in the Kielder Forest, Northumberland, UK. The use of hygromorphs in this particular project has been influenced by the relevance of the material to the locality and the wish of the client (Kielder Water and Forest Park Trust) to deploy it as a means to educate visitors about the environment. This project will not only allow to test the real-world practical viability of hygromorphic systems but also to gauge and ascertain the reception and understanding of the materials on behalf of visitors and users within the local ecological context.

## 4. Recommendations for future research

Long-term testing of 'real-world' applications at an architectural scale should contribute to the future opportunities for large-scale adoption of hygromorphic wood composites. However, there is still a need for further experimental and numerical research to ensure repeatable pre-programmable response and longevity of the materials. A detailed study of the effects of material configurations on the stress states within the composite layers may provide an improved understanding of the reasons for the observed inconsistencies in the cyclic behavior of hygromorphs. This work suggests that hygromorphic wood composites have the potential to enable low-tech low-cost multifunctional passive climate-responsive building systems that address a range of sustainable design considerations.

## 5. Acknowledgements

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